OPERATIONAL MODELLING OF NUTRIENTS AND PHYTOPLANCTON IN THE BAY OF BISCAY AND ENGLISH CHANNEL.

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Abstract

Nitrate loadings to the French coastal waters of the Bay of Biscay and the English Channel have increased from 5 to 10 times during the four last decades, due to runoff on intensively fertilized agricultural watersheds. Eutrophication of this coastal zone is now a recurrent problem, with well-known direct impacts (Ulva "green tides" on beaches, excessive phytoplanktonic blooms responsible for "coloured waters" and bottom hypoxia events offshore), but also indirect enhancement of the toxicity of some phytoplankton species, caused for instance by increased N:Si ratio in the coastal sea. In order to better guide the decision makers about nutrient loading reduction, Ifremer uses the so-called ECO-MARS3D biogeochemical-hydrodynamical model to simulate the present situation in terms of phytoplanktonic biomasses and oxygen concentrations, along with more specific information: concentrations of 3 harmful phytoplanktonic species (Pseudo-nitzschia, Karenia, Phaeocystis) and ASP toxin (domoic acid) in the sea water. The simulations of recent years have been compared favorably to satellite images and field measurements, and an operational version currently runs on the previmer.org site. An original tracking method of nitrogen (or phosphorus) coming from any source allows the assessment of the quantitative role of the 3 main rivers (Seine, Loire, Gironde) nitrogen loads in the phytoplankton blooms. The model points out the bay of Vilaine as very sensitive to bottom oxygen depletion in summer, and can be compared on-line to the automatic measurements coming from the MOLIT buoy. Through the appearance of too high N :Si ratio in the nutrients, the model also provides some explanation to the patchy location of ASP toxin recorded by the REPHY monitoring network.

The French coastal eutrophication in the European context

The terrestrial loadings on the European coastal shelf have varied during the last century in a nearly independent way for the three main nutrient Nitrogen N, Phosphorus P and Silicon Si. Whereas Si remained quasi-constant or slightly declined due to partial trapping by settling freshwater diatoms upstream of dams, P increased until the nineties, and then decreased thanks to polyphosphate banning in detergents and phosphate removal in sewage plants (Billen and Garnier, 2007); N increased continuously during the second half of the 20th century, but began to slightly decrease during the last decade due to European directives.

The first global impact of coastal eutrophication is an increase of phytoplankton biomass in the enriched areas, mainly in the plumes of rivers. In temperate seas, a characteristic of eutrophicated waters is the apparition of additional blooms in summer, between the two classical blooms (the main one in spring and the secondary one in autumn). The sedimentation and decomposition of high phytoplanktonic biomasses in stratified and calm areas may lead to severe oxygen depletions in bottom waters, as in the bay of Vilaine, in July 1982 (Merceron, 1988). Besides these quantitative effects, some qualitative changes in the flora may be induced by the changing balance N/P/Si. In the eastern English Channel and the southern North Sea for instance, undesirable blooms of the Haptophyte *Phaeocystis globosa*, which forms spherical colonies with foam as by-product, invades every spring (April-May) the coastal strip from the Bay of Somme up to Belgium (Lancelot, 1995). These Haptophytes are known to follow the classical early-spring diatom bloom (Rousseau et al., 2002) when a remaining excess of nitrate allows their rapid growth, even if phosphate conditions are low (Lancelot et al., 1987), because this species is able to use organic forms of phosphorus (Veldhuis et al., 1991). Along the Atlantic and English Channel coasts, several harmful species of phytoplankton have been recorded for a while, because they produce diseases in human consumers of shellfishes. Some of them are dinoflagellates (*Dinophysis* sp., *Alexandrium* sp.), and may have been triggered by summer excess nutrient in the coastal plumes, as mentioned by Guillaud and Ménesguen (1998); in case of *Dinophysis* sp., the link between nutrients and the dinoflagellate seems to be indirect, through intermediate ciliates used as preys by the heterotrophic dinoflagellate (Souchu et al., 2013). Recent episodes of long-term Amnesic Shellfish Poisoning have severely hampered the scallop fisheries in the eastern English Channel and the northern Bay of Biscay (first event in December 2004 in Bay of Seine and Brittany, very strong and persistent contamination in the northern Bay of Biscay following the Xynthia hurricane); they are due to domoic acid production by several diatom species belonging to the genus *Pseudo-nitzschia*. Several papers have clearly related the biomass increase of these species to the increase of nitrogen delivery by rivers (Parsons and Dortch, 2002), as well as the enhancement of toxin production by excess of nitrogen availability relatively to silicon or phosphorus (Fehling et al., 2004).

Thanks, first, to the Water Framework Directive WFD (2000), then to the Marine Strategy Framework Directive MSFD (2008), the European Commission has compelled European countries to periodically assess the status of their coastal waters relatively to the eutrophication process (Ferreira et al., 2011). For the WFD, coastal water masses have been delineated following the "1 nautical mile from shoreline" rule, which can miss the most part of wide eutrophicated areas: in a large river plume, the turbidity near the coast and the estuary is often too high to allow strong primary production, whereas enriched surface waters more offshore, after settling of suspended particles, can host very productive communities. For the MSFD, the "ecological status" has to be monitored on the whole shelf, in a few large sub-regions, for which dense sampling at sea becomes too expensive and unaffordable. Modelling the eutrophication on the European shelves then becomes an attractive way to fill the gap, as well as satellite remote sensing.

The ECO-MARS3D tool

The biogeochemical modelling component (ECO-MARS3D) of the French Previmer project of Coastal Operational Oceanography is based on the MARS3D hydrodynamical code (Lazure and Dumas, 2008). The current application to the French Atlantic shelf is based on a regular grid with 4x4 km meshes and 30 sigma levels, which covers the Bay of Biscay, the English Channel and the southern part of the North Sea, up to the Rhine estuary; it extends from 8.13°W to 5.0°E, and from 43.17°N to 52.75°N (Fig. 1). This running version is an extended and re-calibrated version of a first model of the same space resolution, but limited to the Bay of Biscay, which was built as a Previmer demonstrator. This has been run operationally during 6 years (2007-2012) on the previmer.org site, and used also for a long off-line run (1972-2008) for an environmental approach of pelagic fish fluctuations (Huret et al., 2013).

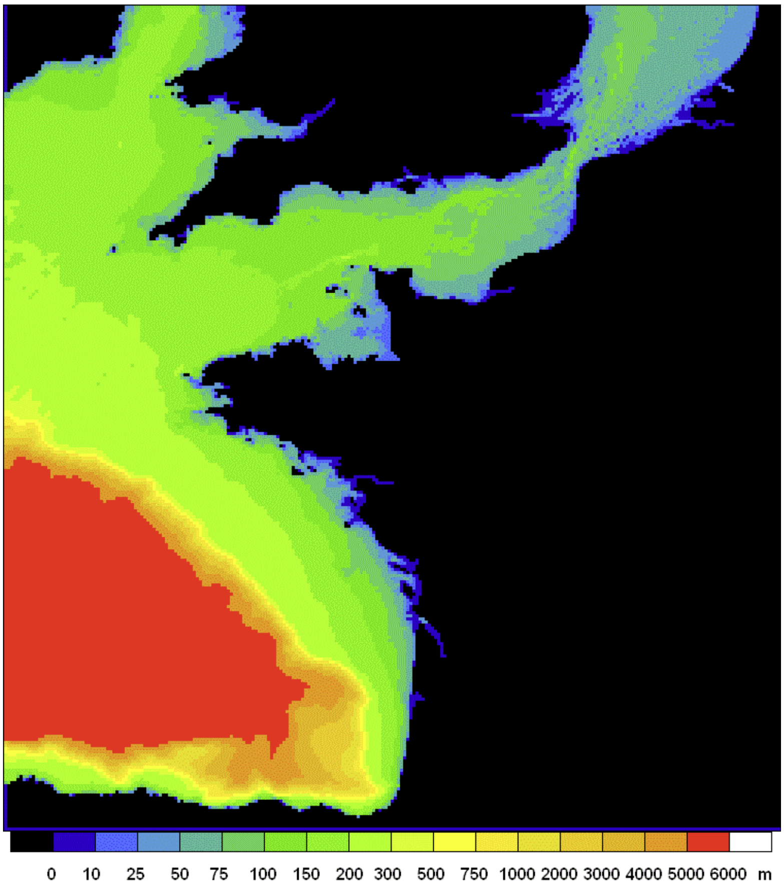


Figure 1: Bathymetry (mesh: 4x4 km) of the English Channel and Bay of Biscay model domain.

Mechanical forcing of the MARS3D hydrodynamical model is made by barotropic sea-level oscillation at the oceanic boundaries (provided by a 2D model covering the whole North-East Atlantic), and wind and atmospheric pressure at the sea surface; these are provided by the Arpege model of Météo-France with a 30 km and 6 h space-time resolution. Measured daily discharges as well as monthly river temperatures are provided on line by the Seine-Normandy, Loire-Brittany and Adour-Garonne River Basin Agencies, for the 5 main French rivers: Adour, Gironde, Loire, Vilaine and Seine. For all the other rivers in the domain, only discrete measurements of flow rates made in recent years are available for validation; in operational mode, the daily flow rate of these rivers is deduced from the measured flow rate of the nearest main river by linear regression. River daily concentrations for inorganic and organic dissolved nutrients are computed from empirical statistical relationships involving flow rate and time fitted to historical data (Guillaud and Bouriel, 2007). Suspended particulate matter is set to the maximum of ambient climatological monthly mean distribution derived from satellite data (Gohin et al., 2005) and the suspended matter brought by the rivers, which is simply simulated as a particulate conservative tracer, with uniform and constant settling velocity. At the open boundaries, all the biogeochemical state variables are imposed following a zero gradient condition.

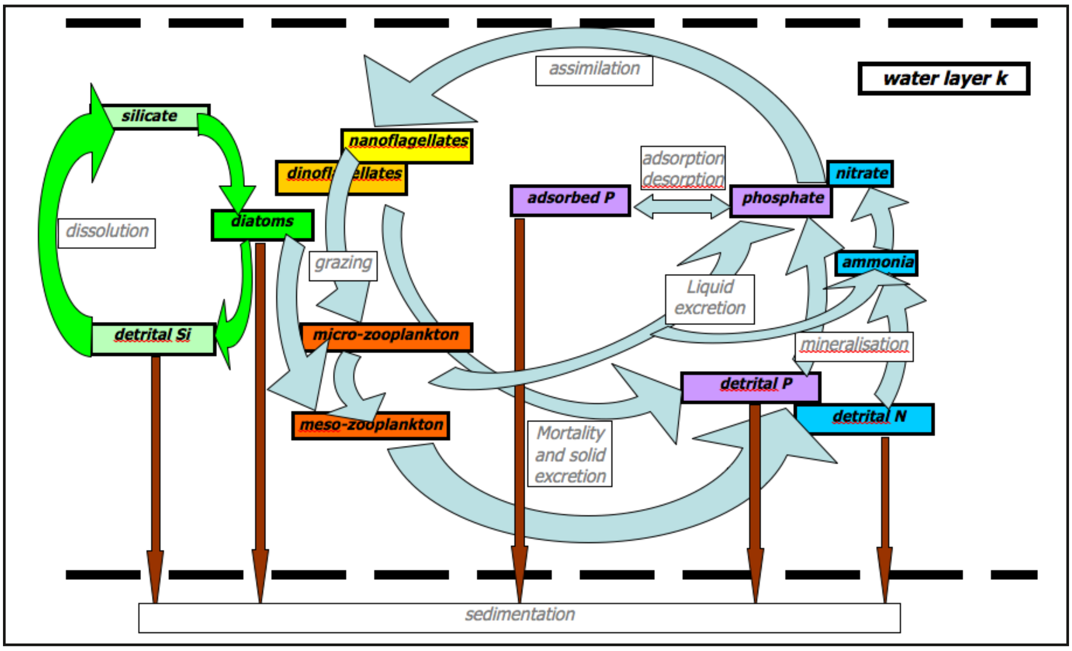


Figure 2: Flow diagram of the biogeochemical model.

The basic biogeochemical model (Fig. 2) contains 17 state variables, describing the nitrogen, phosphorus and silicon cycles and the dissolved oxygen in the pelagic ecosystem. Three limiting dissolved inorganic nutrients are considered: nitrogen, with nitrate and ammonium separately, phosphorus, and silicon. Phytoplankton is divided into 3 groups: diatoms, dinoflagellates and nanoflagellates, with concentrations expressed in nitrogen currency. In order to mimic pigment adaptation to the ambient mean light, chlorophyll is deduced from the nitrogenous state variables of the model by an empirical Chl:N ratio, computed as a Smith-like formula depending on the local extinction coefficient. There are two zooplanktonic components, expressed in nitrogen units: the microzooplankton, which eats nanoflagellates and detrital particulate matter everywhere, along with diatoms in oceanic regions (depth>200m), and the mesozooplankton, which eats diatoms, dinoflagellates and microzooplankton. So, in this model, diatoms do sink, whereas nanoflagellates and dinoflagellates do not (they are considered as able to maintain at any depth in calm water, thanks to motility). Three particulate detrital variables (detrital N, detrital P, detrital Si) close the biogeochemical cycles, and settle in the water column; in the bottom layer, each settling fraction is partially transferred to a fixed state variable, which can give back to the water layer some particulate material through erosion by currents, and some dissolved equivalent after remineralisation.

Some advanced features are also provided on the Previmer website. Three harmful phytoplanktonic species or genus have been added in competition with the three basic bulk phytoplanktonic variables: the diatoms *Pseudo-nitzschia* sp. responsible for Amnesic Shellfish Poisoning of human consumers of infected bivalves, the dinoflagellate *Karenia mikimotoï* responsible for marine invertebrate and fish kills, and the prymnesiophyte *Phaeocystis globosa* responsible for mucus and foam production. For *Pseudo-nitzschia*, following Davidson and Fehling (2006) and Pénard (2009), the importance of the internal Si:N ratio in triggering the toxin secretion led to the adjunction of 2 state variables to the basic nitrogen mass : the silicon mass and the toxin (domoic acid) concentration. The limiting effect of silicon on the growth is now depending on Si:N ratio (Si internal quota) in a Droop's formulation, whereas the N and P limiting effect remain dependent on the water nutrient concentration in a classical Michaelian manner. As in the Davidson and Fehling's model, when the internal Si/N ratio goes below a certain threshold, the continuous secretion of domoic acid is activated; the toxin then decays following a simple first order process. Finally, in order to highlight the respective roles of the three main tributaries of the domain in sustaining the phytoplanktonic production, a numerical tracking technique (Ménesguen et al., 2006) has been applied to the inorganic nitrogen loads of the Seine, Loire and Gironde rivers, allowing to track dynamically the fraction of phytoplanktonic nitrogen fuelled by these three tributaries.

Numerous data have been gathered for validation purposes. They come mainly from REPHY, MAREL and SOMLIT monitoring networks for the French coastal zone, from CEFAS and WCO (Western Channel Observatory) for the U.K coastal zone, from the BMDC (Belgian Marine Data Center) for the Belgian coastal zone, as well as from some French oceanographic cruises (MODYCOT). A unique time-series of dissolved oxygen in surface and bottom waters has been measured in the bay of Vilaine by the MAREL buoy named "MOLIT". NOAA AVHRR measurements of Sea Surface Temperature and MODIS colour measurements are collected by Ifremer's Nausicaa browser automat and processed thanks to the OC5 algorithm (Gohin et al., 2002), with a subsequent merging of images collected during the 4 last days, in order to partially fill the holes caused by cloud covering.

Some results

A detailed validation of the hindcasts of this wide application of the coastal ECO-MARS3D is under progress. A first global overview of the surface chlorophyll can be obtained from the comparison between the mean values during the growing season (March to October) obtained from satellite images and from the model respectively (Fig. 3). The computed mean annual chlorophyll concentration reproduces the great difference between the productive French coastal strip of the Bay of Biscay and the eastern English Channel (enriched by the nutrient loadings of Gironde, Loire, Vilaine and Seine rivers) and the poor zones located over the abyssal plain, on the outer shelf or in the western English Channel; but the scatterplot clearly shows a strong dispersion of simulated values at large measured value, i.e. in front of estuaries.

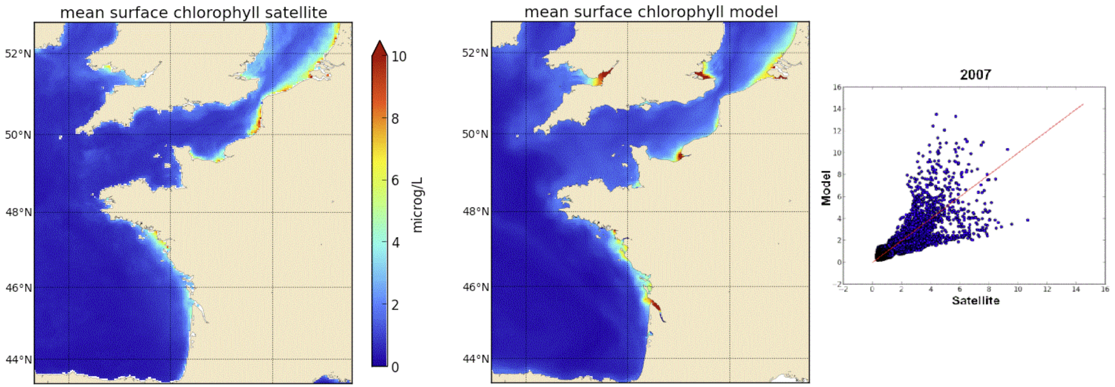


Figure 3: Observed (MODIS satellite) and simulated mean surface chlorophyll during the period March-October 2007.

Even when nutrients are correctly simulated, this damped behaviour of simulated chlorophyll relatively to the observed one can be retrieved in the decadal validation of the simulation of main nutrients (NO_3, NH_4, PO_4, $Si(OH)_4$) and total chlorophyll at the Cabourg station (Bay of Seine, eastern Channel), which can be considered as presenting some characteristic features of an eutrophicated place (Fig. 4)

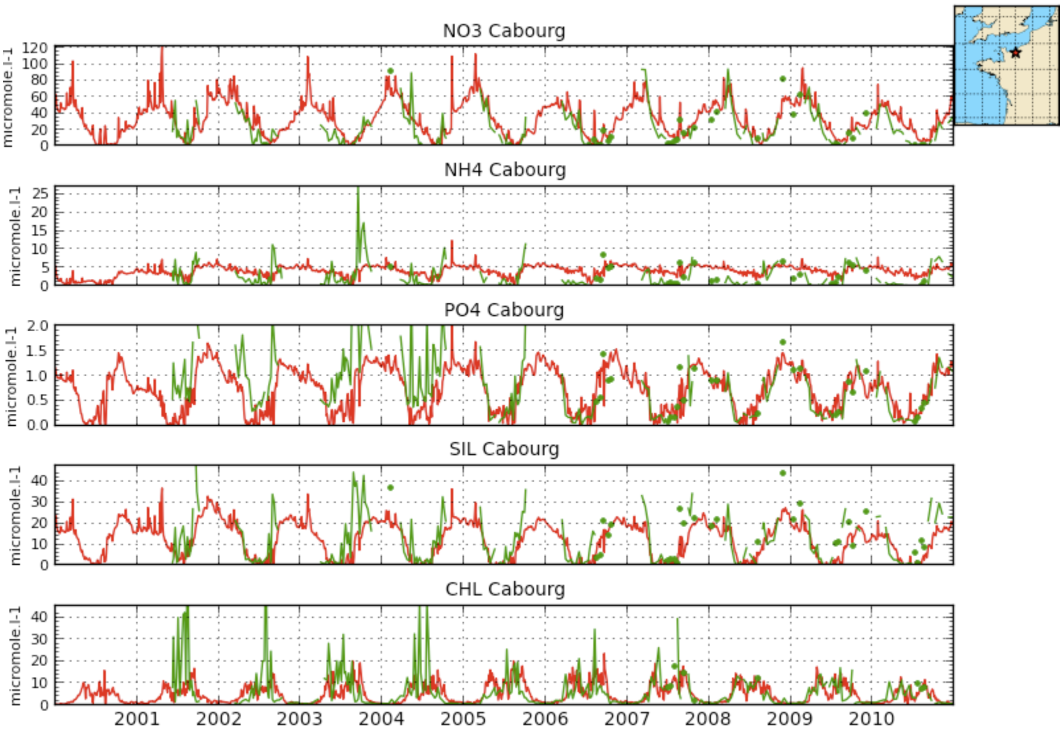


Figure 4: Decadal validation of the simulation of main nutrients (NO3, NH4, PO4, Si(OH)4) and total chlorophyll at the Cabourg station (Bay of Seine, eastern Channel)

As mentioned earlier, oxygen depletion in bottom waters is a crucial parameter in defining the ecological status of water mass relatively to the eutrophication process. The model has been validated with the unique long and high frequency series of bottom oxygen concentration measured by the Previmer's MOLIT buoy in the bay of Vilaine. Even if the model fails to reproduce some short episodes of over-saturation, especially in the surface layer, it reproduces the gradual decrease of oxygen concentrations measured near the bottom during spring and summer (Fig. 5), which can lead to repeated episodes of hypoxia down to 2mg/L O_2, which is clearly considered as being deleterious for animal physiology (Gray et al., 2002).

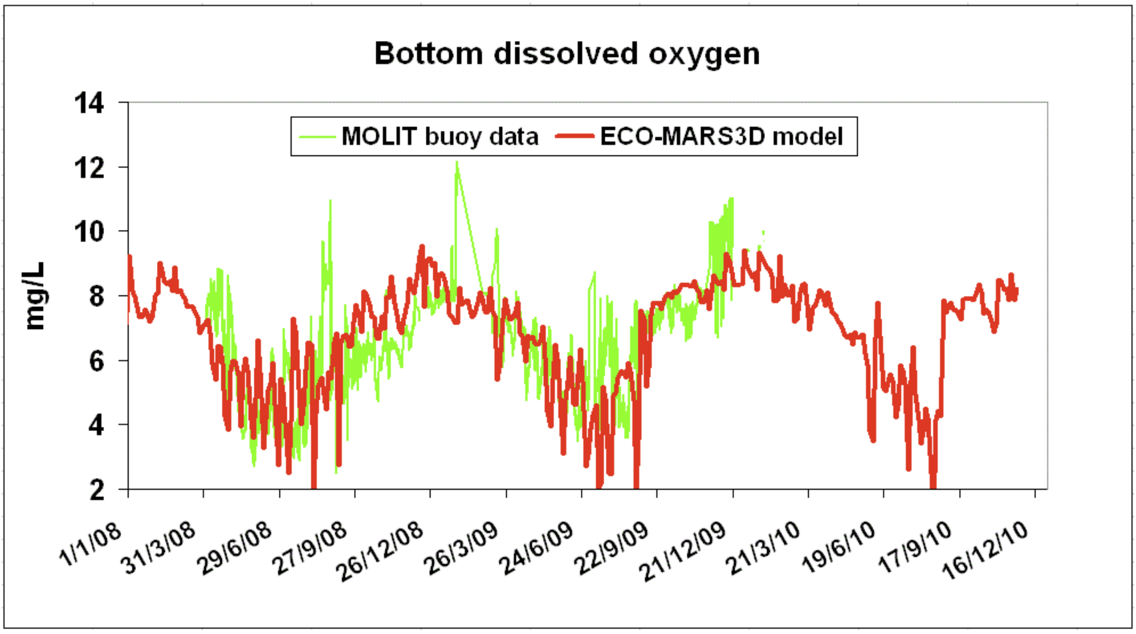
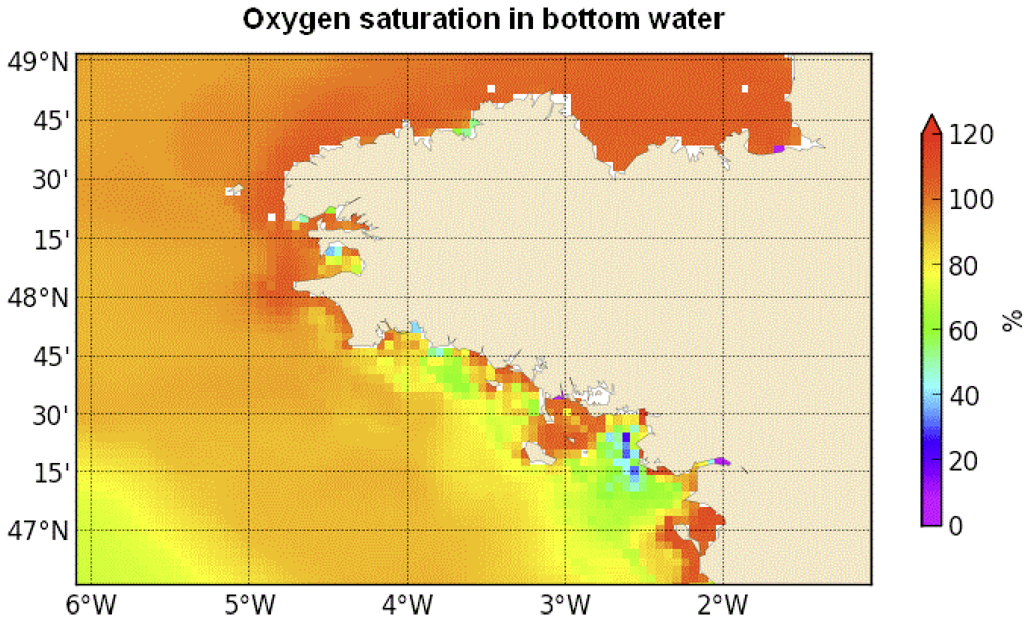


Figure 5: Measured (MOLIT buoy) and simulated oxygen concentration in bottom water in the Vilaine bay (French Atlantic coast).



Since 2007, the model has provided on the previmer.org website daily maps of bottom oxygen saturation in southern Brittany, which reveal (Fig. 6) that the bay of Vilaine is the hot point of a more extensive area subject to recurrent hypoxia during summer. A recent study based on the same ECO-MARS3D results has put forward the hypothesis that some acute hypoxia episodes may trigger high mortality (e.g. in August 2006) of the ground-farmed oysters of the nearby bay of Quiberon (Stanisière et al., 2013).

Figure 6: Simulated oxygen saturation in bottom waters on August, 1st, 2009.

Modelling the change induced in phytoplankton biodiversity by eutrophication is the future challenge for biogeochemical models. A first limited step in that direction has been recently made on the Previmer operational version of ECO-MARS3D model by introducing three types of HAB species (Harmful Algal Blooms species) which are commonly found on some parts of the French Atlantic-Channel coast (Fig. 7). These additional components compete for light and nutriments with the three basic bulk components, but each of them has narrower ecological preferences than it non-specialised bulk homolog. The *Pseudo-nitzschia* diatom component, for instance, has a temperature optimum about 14°C and lower half-saturation constants for nutrient uptake that allows it to bloom in May-June, i.e. after the decay of the main diatom spring bloom. The simulated ASP toxin content of *Pseudo-nitzschia*, caused by silicon depletion of cells, reproduces the spatial distribution of toxicity measured in shellfishes by the REPHY monitoring network and its apparent lack of correlation with the abundance of *Pseudo-nitzschia*. For instance, in contrast with the southern Brittany, the northern Brittany remains almost free of contamination in spite of a common spring occurrence of this diatom genus.

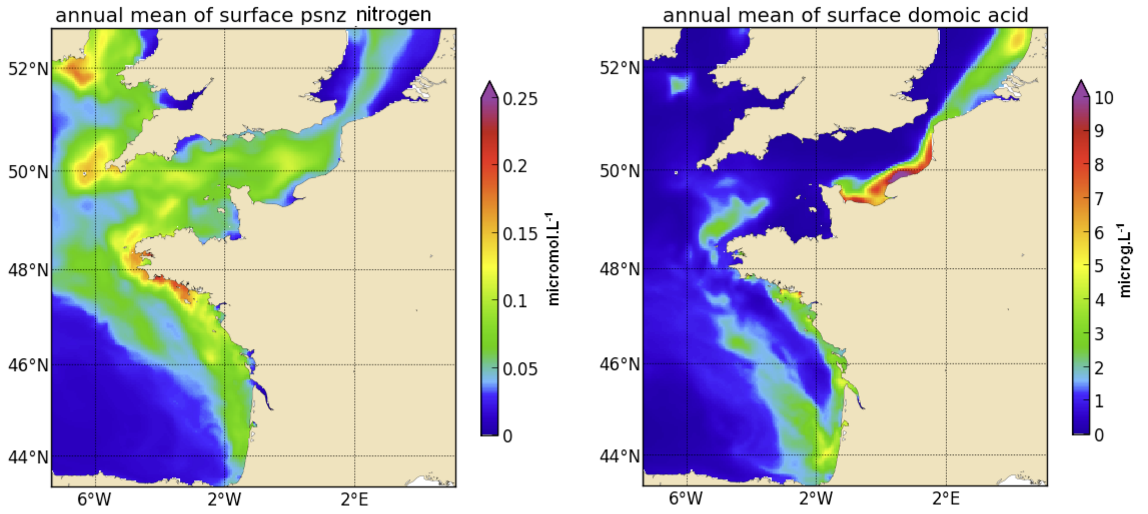


Figure 7: Simulated mean annual distribution of Pseudo-nitzschia biomass (left) and ASP toxin-domoic acid (right)

Improving the ecological status of eutrophicated water masses (Water Frame Directive and Marine Strategy Frame Directive) or moving from (potential) problem to non-problem areas (OSPAR) implies assessing the responsibility of any terrestrial input of nutrient in the coastal zone enrichment. OSPAR commission has a particular interest in the transboundary transport of nutrients, and the ICG-EMO working group has devoted a special session to its modelling (OSPAR, 2009). Thanks to a tracking and aging technique applied to the entire nitrogen cycle in the model, the Previmer website provides daily maps of the part of phytoplankton nitrogen which comes respectively from the Seine, Loire and Gironde rivers, along with the mean time elapsed from its entrance in the marine ecosystem. These maps bring to light the long-range marine imprint of big rivers, which may change location following winds and flow rates (Fig.8 left & middle), and the relatively long residence time of these inputs over the continental shelf. Roughly speaking, the Seine nitrogen imprint on phytoplankton entering the North Sea is about one year old, whereas the Loire imprint is three years old (Fig.8 right).

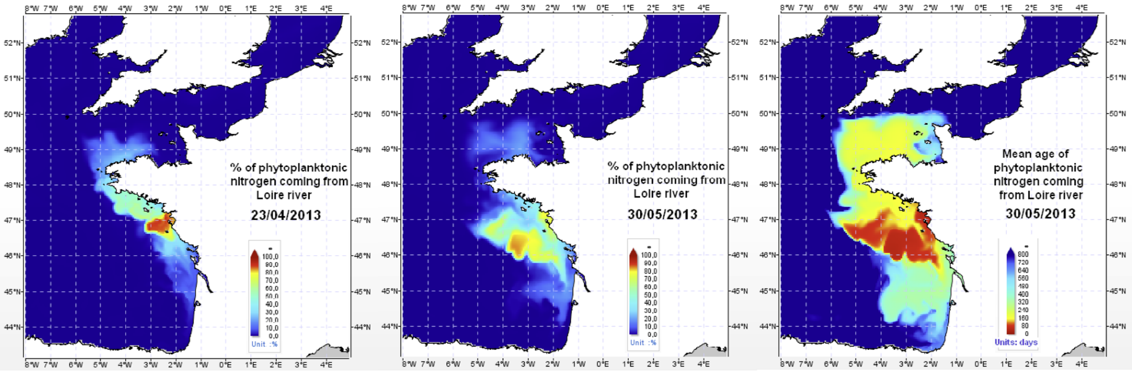


Figure 8: Distribution of phytoplanktonic nitrogen coming from Loire river on April, 23th and on May, 30th, with its mean age at this last date.

Conclusion

An ecological model of the nutrients and phytoplankton on the Bay of Biscay/English Channel area (i.e. covering a large part of the IBI-ROOS domain) has been validated on a ten year period by comparison to various data (remotely sensed images of SST and surface chlorophyll, samples from monitoring stations, data from a buoy). Globally speaking, the model was able to reproduce the geographical pattern as well as the seasonal mean time course of nutrients and total chlorophyll. It reproduces also the occurrence of strong hypoxia events in the bottom layer of the bay of Vilaine, as observed by an automatic buoy. Since the end of 2013, this model has been turned into an operational mode, for the previmer.org website, to replace the previous versions limited to the Bay of Biscay shelf and Brittany. Some new products have been added to help the understanding of the influence of the three main French rivers (Seine, Loire, Gironde) on the global phytoplankton production, as well as on the triggering of some HAB episodes (foam produced by *Phaeocystis*, ichtyotoxin from dinoflagellate *Karenia* and amnesic toxin from diatoms *Pseudo-nitzschia*).

Apart from the immediate interest of such on-line information, this operational tool does provide over the years a growing bank of daily simulated situations, which will be used to build a statistical description of the “mean” nutrient and phytoplanktonic annual cycle in these coastal areas, as well as to define what can be designated as being “extreme” events. This information will feed the Water Frame Directive report for the French water masses, and will help to asses the ecological status of the French sub-regions defined in the Marine Strategy Frame Directive.

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